COMPARISON OF METHODS FOR DETERMINING ADVISORY SPEEDS ON HORIZONTAL CURVES

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ABSTRACT

Horizontal curves are an integral part of the highway alignment. However, a disproportionately high number of severe crashes occur on them *(1)*. One method transportation agencies use to reduce the number of crashes at horizontal curves is the installation of curve warning signs which post an appropriate advisory speed. Appropriate curve advisory speeds can be determined using several methods. The purpose of this research was to find the most efficient and accurate data collection method for determining curve advisory speeds. Several processes were developed and tested, including the Curve Advisory Reporting Service (CARS), Texas Roadway Analysis and Measurement Software (TRAMS), the use of Highway Information System (HIS) data, and an ArcGIS-based manual analysis. The results of these various methods were then validated against Digital Ball-Bank Indicator (DBBI), which is a currently accepted method. Comparison and evaluation showed that CARS seemed to be the most promising new method, while the DBBI was favored as the standard. This study will allow researchers to develop advisory speeds that can assist in properly signing horizontal curves, which previous research suggests results in a safer driving experience.

1. INTRODUCTION AND BACKGROUND

In the United States, severe crashes occur in disproportionate numbers on horizontal curves. Each year, approximately 33,000 fatalities result from crashes, with 25 percent of these taking place on horizontal curves *(2)*. This is a number that the Kentucky Transportation Cabinet (KYTC) sought to improve and, to that end, contracted the Kentucky Transportation Center (KTC) to examine the problem. Preliminary research found that the high number of curve crashes could be mitigated by slower speeds: approximately 85 percent of the fatal crashes that occur on horizontal curves involve roadway departures due in part to vehicles moving at excessively high speeds *(3)*.

Warning signs posted near curves alert drivers to approaching changes in road geometry and encourage speed reductions, but fail to establish an enforceable speed limit for curves *(2)*. Furthermore, numerous studies have shown that drivers do not change their behavior in response to warning signs nor do they comply with recommended speeds at horizontal curves *(3)*. Evidence of this non-responsiveness is supported by curve crash statistics *(2)*. Policies for setting advisory speeds vary from state to state; within individual states, complex methods are used to calculate advisory speeds for each curve. Researchers have suggested that inconsistent advisory speeds may contribute to crashes at curves.

As such, there is a need for a clear, consistent method to set advisory speeds at horizontal curves. The method should let engineers identify when curve warning signs and advisory speeds are needed and facilitate the selections of an advisory speed that is consistent with driver expectations *(2)*. This should convey a realistic message establishing driver expectancy and promote effective roadway operations *(3)*. Equation 1 may be used to calculate the design speed for a curve.

$$v_i = \sqrt{15(r)(e+f)}$$

$$\begin{aligned} &v_i = curve\ design\ speed \\ &r = curve\ radius, ft; \\ &e = superelevation\ rate, decimal\ between\ 0\ and\ 1; \\ &f = side\ friction \end{aligned} \qquad (1)$$

KYTC developed a priority list of sites based on the number of road departure crashes that have occurred. This list included approximately 25 percent of the state-maintained road system. The Cabinet issued a statewide curve signing plan that was awarded to three consulting firms: Neel-Shaffer, Gresham, Smith and Partners, and HDR, Inc. Each consultant firm determined the appropriate curve advisory speed for the routes in the districts they were assigned. Each firm was trained to use the digital ball-bank indicator method. This method is generally viewed as an effective and accurate procedure and is commonly used by transportation agencies around the United States.

2. AVAILABLE METHODS

A number of methods have been developed to calculate curve advisory speeds. Methods currently in use include the direct method (use of the design speed equation), the ball-bank method (using either the digital or traditional ball-bank indicator), the Curve Advisory Reporting Service (CARS) System, and the Texas Roadway Analysis and Measurement Software (TRAMS). Two other methods involve leveraging data that KYTC currently gathers. They were evaluated using Highway Information System (HIS) data and a software solution using ArcGIS (the Arc Method). Each method relies on different procedures and comes with unique advantages and disadvantages. This study evaluated the six methods listed above, focusing on their practicality, efficiency, and cost-effectiveness. The following sections describe the execution of each method.

2.1 Direct Method

The *direct method* is based on field measurements of a curve's radius and superelevation. An equation is used to estimate the curve radius based on the offset at the middle of a 100-foot chord. The superelevation is measured at several locations through the curve. The maximum superelevation is used in the design speed calculation. (*Eqn. 1)*

2.2 Digital Ball-Bank Indicator

The *digital ball-bank indicator (DBBI) method* is based on a set of field driving tests that measure lateral acceleration and driver discomfort as vehicles travel through the curve. The main steps consist of collecting data via a digital or traditional ball-bank indicator and using those data to determine curve advisory speed *(1,4).*

The term *ball-bank indicator* refers to an inclinometer that is used to determine safe curve speeds for horizontal curves *(5).* The traditional device consists of a curved glass tube filled with liquid, which is mounted in a vehicle. A weighted ball floats in the glass tube. As the vehicle travels around a curve, the ball floats outward in the curved glass tube. Movement of the ball is sensed by a digital reader and reported to the user as a measurement in degrees of deflection. The magnitude of deflection reflects the combined effects of superelevation, lateral (centripetal) acceleration, and vehicle body roll *(1).*

Specific criteria for the ball-bank method vary, but are based on lateral acceleration and a measure of driver discomfort. The goal is to minimize driver discomfort as vehicles travel through curves. Engineers consider minimal driver discomfort as indicative of a safe speed, although it is worth noting that driver discomfort may vary with the skill of the driver. *(1,4).* The Manual on Uniform Traffic Control Device (MUTCD) 2009 edition set the criteria for the ball-bank indicator as follows:

- 16 degrees for speeds of 20 mph or less
- 14 degrees for speeds of 25 to 30 mph
- 12 degrees for speeds of 35 mph and higher *(6).*

Because this method relies on field comparisons of speed and displacement of a ball-bank indicator, it is imperative that the test vehicle's speedometer is accurate. The speedometer should be calibrated using a radar gun, a laser, time-distance comparisons, or other method. The digital ball-bank indicator (DBBI) should be calibrated as well by mounting it so that it displays a 0-degree reading when the vehicle is stopped on a level surface. Typical passenger cars are best suited for this test, because other vehicles may affect the amount of body roll measured *(1).*

A vehicle should make several passes through a curve to ensure the accuracy of the ball-bank indicator reading. Drivers should begin by driving at a fairly low speed; speed is incrementally increased for each iteration of the test. On each test run, the driver must reach the test speed at a specified distance in advance of the curve's entrance and maintain that speed throughout the length of the curve. The test is repeated until the displacement of the ball-bank indicator exceeds the thresholds listed above *(1).*

The curve advisory speed should be set at the highest test speed that *does not* result in a ball-bank indicator reading above the acceptable level. The advisory speed chosen, therefore, is a product of the roadway geometry and the digital ball-bank indicator reading *(1).* Speed limit only affects the advisory speeds if the estimated speed for that curve is less than the speed limit for the road.

2.3 Curve Advisory Reporting Service (CARS)

The Curve Advisory Reporting Service (CARS) System is a road survey system that automatically records vehicle activity and determines recommended safe curve speed. Developed by Rieker Incorporated, it is marketed as the next generation ball-bank indicator. The GPS-based configuration lets users perform continuous road surveys without stopping. The system is mounted on the dashboard while the vehicle travels with traffic, requiring only one pass to collect the necessary data *(7).* There are two main components: a tablet application and a web portal *(8).* The system captures data for several parameters, including curve radius and superelevation, which assist in deriving a safe curve speed *(7).*

The system functions similarly to the digital ball-bank indicator in that it measures vehicle movement to estimate various road features. GPS technology provides more accuracy than traditional ball-bank indicators *(8).* The CARS package consists of a GPS ready Digital Ball-Bank Indicator (the RDS7-GPS-PRO), a compatible Windows Tablet, Rieker proprietary CARS Recording Software, all necessary cables, and a vehicle tablet mount *(7).* Drivers decide when to begin recording with the device, but it requires no user inputs once the recording has begun. Its operation requires only one person so they can focus their attention on driving.

The CARS system automatically calculates the curve advisory speed by analyzing the data collected *(7)*. The tablet displays the calculated speed.

2.4 Texas Roadway Analysis and Measurement Software (TRAMS)

The Texas Roadway Analysis and Measurement Software (TRAMS) Program utilizes deflection of a ball-bank indicator, speed, and geometric data for the curve and the highway, then plots the data on a map using GPS coordinates *(3.)* Similar to CARS and other methods reliant on GPS, this program collects geospatial data and then exports them to a second software tool which calculates advisory speed *(9)*.

The equipment required for the TRAMS program includes a GPS receiver to estimate geospatial attributes, a laptop computer to facilitate data analysis, and an electronic ball-bank indicator (which is optional, but provides a simple way to estimate superelevation rate) *(10)*. The TRAMS program requires a driver to initiate data collection. Then, after they drive the vehicle through a curve, the software calculates curve radius, superelevation rate, and deflection angle from the data streams *(9)*. Advisory speed and traffic control device selection guidelines can be determined using the radius and superelevation rate estimates, which are calculated in the Texas Curve Advisory Speed (TCAS) Excel spreadsheet (this is included in the software package) *(10)*. Processing entails dividing the curve into a series of segments and calculating the length, deflection angle of each segment, and radius. This method often introduces excess noise into the data, and requires some filtering before the program is able to determine a good estimate of radius. A Kalman filter or regression model can be used to filter the data. Superelevation for each segment is calculated using the average of the ball-bank readings recorded as the vehicle travels along each combined segment. Once all the geometric data for each curve segment has been calculated, TRAMS identifies the segment with the smallest radius. This radius, superelevation rate, and deflection angle are then used to determine the advisory speed *(9)*.

2.5 Highway Information System

Unlike the other methods described, the use of Highway Information System (HIS) data is not an MUTCD-approved method to evaluate curves. However, HIS data is readily available and offers a way to evaluate curves without driving them. KYTC's Division of Planning provides a GIS shapefile that transportation engineers can use to gather information. The shapefile includes information about roadway curves throughout the state. Of critical importance is a dataset that contains the geometry of each curve in degrees. This value can be used in equations to calculate advisory speed, with assumptions made for the superelevation.

2.6 Arc Method

The final method evaluated relies on data previously collected by KYTC. In fact, using data that have already been collected is a key strength of this method. Data collection vans have been used throughout the state to gather data for maintenance and safety operations; data collection occurs at least once every two years. Collection vans include cameras, GPS, tools to measure inertia and pavement roughness, and Mandli hardware and software.

The Mandli software reports curve data at user-selected intervals in these files. Results of the curve report include GPS, county, route, milepoint, curve radius, maximum superelevation. Data is plotted in ArcGIS, which results in data points spaced at 5-foot intervals. The data points were used to measure the radius of curvature and calculate superelevation, which are then used in advisory speed calculations.

3 METHODOLOGY

3.1 Data collection

The goal of this study was to identify the most cost-effective and efficient data collection method to employ at the statewide level. Several sites were chosen across the state and various methods were used to determine advisory speeds. There were twelve routes containing a total of 156 curves, selected to provide various types of roadway geometry. The digital ball-bank method, CARS, and Arc were used on all curves. HIS data were also obtained for all curves. Furthermore, four of the routes were analyzed using additional methods. Table 1 summarizes which methods were used at the chosen locations, and includes relevant notes on data collection for each method as well.

TABLE 1 Methods and Locations

Route	County	Direct	CARS	TRAMS	HIS	Arc
US 60	Clark	X			X	X
KY 11	Powell	X			X	X
KY 420	Franklin		X		X	X
KY 1973	Fayette	X	X	X	X	X

3.1.1 The Direct Method

The Direct Method was used at three locations — in Fayette, Clark, and Powell counties. This method is the most time consuming, and therefore it was not pragmatic to use this method for every site. Because of its time-intensive nature, it would not be an appropriate method to analyze a large number of curves with. Further, the MUTCD approves of other, more efficient data collection methods. To execute this method, the curve radius was calculated by using a formula (with the middle ordinate of a 100-foot chord) and measuring the superelevation. Equation 1 was used to calculate curve design speeds.

3.1.2 Digital Ball-Bank Indicator (DBBI) Collection Process

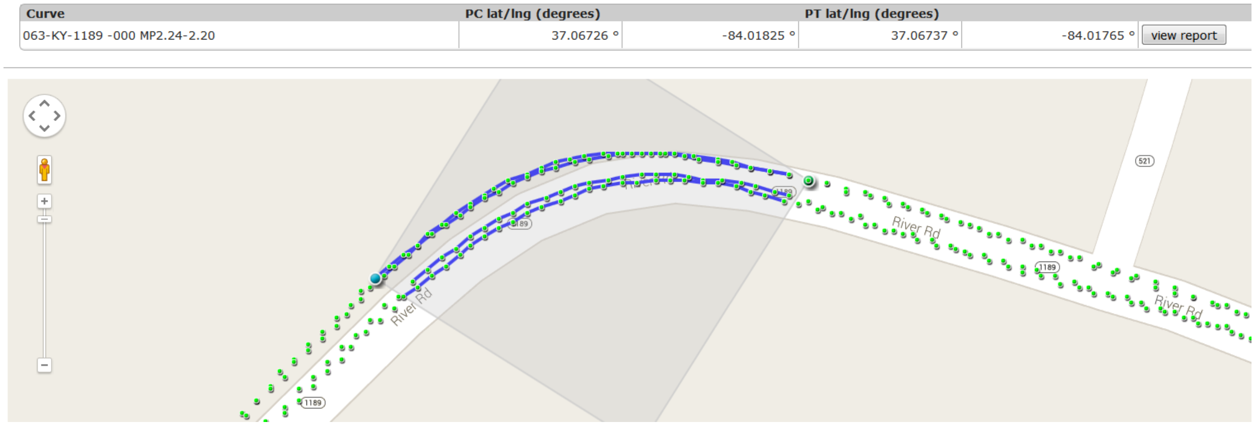
Data for this method were collected using a process developed by the Kentucky Transportation Center (KTC) — it is currently Kentucky's accepted method for calculating advisory speeds on curves. KTC has developed a training course that instructs participants on setting advisory speeds. The course follows the MUTCD and all curve advisory speeds are calculated using MUTCD criteria. Officials initially drive the road in both directions at a speed *5 mph less* than the posted speed limit to identify curves where an advisory speed of *10 mph or lower* than the speed limit is warranted. An alarm on the instrument goes off when a given angle has been reached, indicating the MUTCD criteria has been equaled or exceeded. Then, for each curve identified at the initial test speed, officials should drive the curve in each direction, adjusting the speed at 5-mph increments until a measurement less than or equal to the alarm angle for that speed is reached (different advisory speeds may be set for opposing directions). The advisory speed is set at the speed (in 5 mph increments) below the test speed at which the alarm angle is exceeded.

3.1.3 CARS Collection Process

After establishing an evaluation agreement with Rieker, Inc. KTC was able to use the CARS system. Researchers obtained training for data collection and software use directly from Rieker. The training included an in-field use of the CARS system as well as a demonstration of the web-based software. Rieker suggested driving roadway segments twice in each direction — resulting in four passes per curve. On some curves, additional passes were used to analyze the consistency of the results. CARS was used on a corridor previously measured by Rieker and a Kentucky consulting firm (Neel Schaffer). The CARS system was installed in a vehicle — including a GPS receiver, DBBI, and a tablet. Before the driver started on a route, the posted speed limit was entered into the system. No further driver inputs were required after this.

After data collection, the system can upload data to Rieker's servers if there is an internet connection available. Once uploaded, the web-based software processes the data. All of the collected data are viewable using the web application. On the website, users need to identify each curve with a polygon tool that marks the points of tangency and curvature. This process can be subjective but the goodness of fit metrics can be used to ensure consistent results. A value of over 98 percent is a good indication of a curve with a high degree of fit. Figure 1 illustrates the curve selection process.

FIGURE 1 Example of CARS Curve Selection using Polygon Tool.



After the curves have been identified, the CARS system calculates the advisory speed for each curve — one result for each direction. It should be noted that the GPS points (the green dots in Figure 3) are spatially joined to an invisible layer that includes the route's linear referencing data (county, route and milepoint). This is an essential process that assists in identifying unique curves and in comparing results to those derived from other methods. Figure 4 is an example analysis report the CARS system generates, with discrete records for each pass.

3.1.4 TRAMS

The TRAMS software was only used to analyze a portion of a single route (KY 1973 in Fayette County). The data used had been collected as part of an earlier project. It was included for comparison purposes. This system uses a GPS receiver and a DBBI both connected to a laptop.

At the start of a route, a unique ID was entered into the system to identify the first curve. This ID was used to create an output file. Care was taken to keep track of the IDs so that the curve could later be identified by milepoint. Indicators display if there is a connection to the DBBI and if the GPS is receiving a good signal. The user presses the spacebar at the start and end of the curve while the driver drives the route.

Some helpful direction came from one KYTC district that has experience with the TRAMS system. It was recommended that the user drive 10 to 15 mph below the speed limit. All of the roads in an average sized county, with ADT values of 1000 or more, should be able to be evaluated in two to three days. A couple hours are required to transfer data into Excel and obtain mile points and advisory speeds. The accuracy of this method has been checked several times by comparing its results to those acquired using the traditional ball-bank indicator. The results have proven very accurate. The only problems have been the occasional loss of a GPS data and the failure to collect and record data on a few curves. Those curves were subsequently re-evaluated. The procedure has been efficient. So far, advisory signs have been posted in five counties using data from TRAMS, and two more are ready for sign installation. The district has not compared TRAMS with CARS. We recommend that staff evaluate CARS as there appear to be significant differences between procedures used in TRAMS compared to CARS.

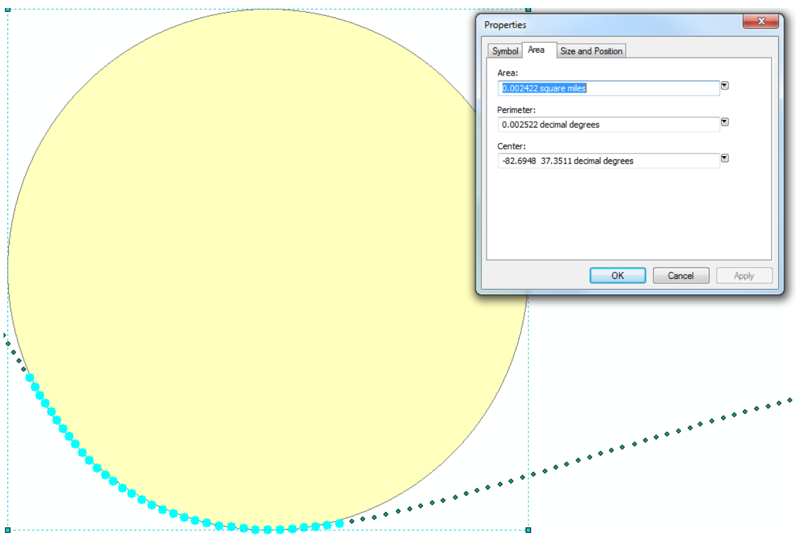
3.1.5 Highway Information System

This is not a MUTCD-approved method to determine advisory speeds. However, KYTC already collects these data so it was logical to determine whether radius data could be used to calculate advisory speeds. Superelevation data obtained from the Arc Method (see below) were used because the HIS database lacks this information. These data are already referenced by county route and milepoint, so they were easily matched to data collected using other methods. Equation 1 was used to calculate advisory speeds using the radius from HIS. Only one radius was available per curve (i.e., the impact of travel direction was not factored in), however, superelevation data for each direction were available. As such, two advisory speeds were calculated per direction. The approach speed for all curves was 55 mph so a side friction value of 0.2 was used.

3.1.6 Arc Method

Researchers evaluated this method to determine if existing data could be used in lieu of field data collection. Mandli Communications data were plotted in ArcGIS as data points along each point included the maximum superelevation, the direction of travel, and linear referencing data. The data points were filtered to show only one direction at a time, which allowed researchers to make a separate calculation for each direction. The start and end of a curve were identified using a method similar to what the CARS System employs — by highlighting the data points (see Figure 2).

FIGURE 2 Example of the Arc Method Curve Selection Process.



Highlighted data points were also used to fit an osculating circle to the curve. A circle was drawn in ArcGIS and resized until it aligned with the highlighted points. The area of the circle was used to calculate a radius. Superelevation varied along the curve but after some trial and error, researchers eventually determined that the median superelevation provided the most consistent results. This process was repeated for each curve and for both directions. Superelevation and radii values were referenced by county, route, and milepoint.

As before, advisory speeds were calculated using Equation 1 and a side friction value of 0.2. Advisory speeds were calculated for each curve twice because radius and superelevation were available for each direction.

3.2 Reconciliation of Various Methods

One of the biggest challenges in comparing advisory speeds calculated using different methods was reconciling errors that mismatched the curves. Several checks were used to ensure accuracy. Visual inspection (via Google Street View) was needed to verify a curve's location since some identified location via midpoint and others via starting and ending mile point. Any curves not identified by all methods were removed. In curves marked with a *winding road* sign, researchers had to take care to match the advisory speed to the curve and make note of the curve within the winding road with the lowest advisory speed. HIS data were used to order the curves.

4 RESULTS

KYTC officials requested that KTC identify a cost-effective, accurate, and consistent method to determine curve advisory speeds for Kentucky roads. The digital ball-bank indicator (DBBI) method is currently used throughout the state. KTC evaluated three alternative methods in detail: CARS, HIS, and ARC. The Direct Method was not evaluated in great detail because it is more time consuming than the other methods. Also, TRAMS method was only used for comparison due to the software being out of date.

The subsequent discussion examines two parameters collected by the various methods: curve advisory speed and radius of curvature. The DBBI method does not provide a curve radius. Ultimately, the curve advisory speed is the most import result. However, the curve radius is the most influential parameter in curve advisory speed calculations (compared to side friction and superelevation).

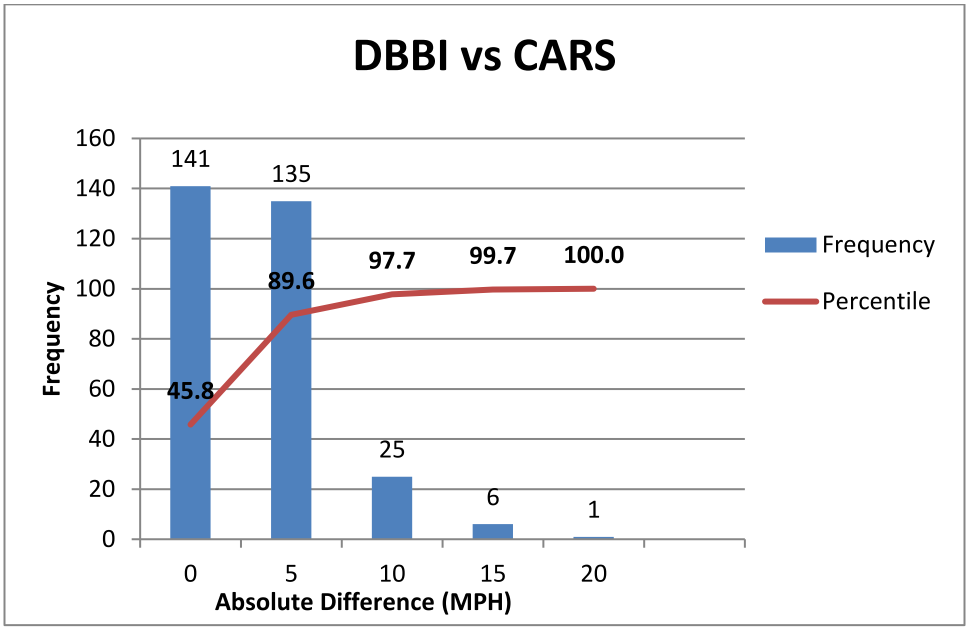
Because it is currently in use, results from the DBBI method were used as a baseline to compare the CARS, ARC, and HIS methods. Each method produces a curve advisory speed rounded down to the nearest 5-mph increment. Advisory speeds derived from the DBBI were compared to those on the CARS report as well as those calculated using ARC and HIS. The absolute difference in calculated advisory speeds was computed for each curve, direction, and method. In other words, researchers found the difference between advisory speeds calculated using CARS, ARC, and HIS methods, respectively, and those obtained from DBBI. Results for ten counties were tabulated to show radii, superelevation, and advisory speed for each curve. Table 2 on the following page shows an abbreviated version: just one of the counties that was studied. Other counties showed relatively similar results, so are not included here for the sake of concision.

TABLE 2 List of Curves and Resulting Advisory Speeds

FAYETTE COUNTY									ADVISORY SPEED (MPH)				RADIUS (FT)			
ROUTE		BEG MP	END MP	CURVE CLASS	SIGN TYPE	PASS	TURN DIRECTION	SIGN	DBBI	CARS	HIS	ARC	CARS	HIS	ARC	MEDIAN SUPER
KY	1973	0.230	0.270	D		1	L		35	35	40	25	357	637	269	0.01
KY	1973	0.430	0.490	D		1	R		40	35	45	40	395	490	363	0.08
KY	1973	0.610	0.690	D		1	L		35	40	45	40	392	477	409	0.07
KY	1973	0.840	0.880	C		1	R		55	45	55	35	677	909	372	0.03
KY	1973	1.320	1.370	C		1	R		40	40	55	30	478	895	262	0.04
KY	1973	1.970	2.000	F		1	L	20	15	15	20	10	61	151	65	0.02
KY	1973	2.010	2.040	F	4	1	R	20	20	15	20	15	115	151	75	0.06
KY	1973	2.960	3.010	E		1	R		30	30	40	25	265	406	199	0.05
KY	1973	3.620	3.690	C		1	R		40	40	50	35	598	744	380	0.04
KY	1973	4.270	4.310	D		1	R		40	45	40	35	722	556	441	0.04
KY	1973	5.120	5.150	C		1	L		35	40	50	25	739	954	311	0.01
KY	1973	7.360	7.410	A		1	L		50	50	55	35	776	2291	644	0.00
KY	1973	9.740	9.780	C		1	R	45	50	45	55	45	570	690	510	0.08
KY	1973	11.180	11.310	D		1	L		40	50	40	50	970	512	955	0.02
KY	1973	11.350	11.400	E		1	R	25	25	25	30	30	205	258	203	0.07
KY	1973	11.490	11.540	D		1	R	35	40	40	45	40	479	441	384	0.08
KY	1973	11.650	11.770	D		1	L	35	35	35	40	35	396	455	344	0.05
KY	1973	0.230	0.270	D		2	R		35	35	50	30	412	637	269	0.05
KY	1973	0.430	0.490	D		2	L		40	40	45	40	309	490	377	0.07
KY	1973	0.610	0.690	D		2	R		35	35	45	40	374	477	402	0.07
KY	1973	0.840	0.880	C		2	L		55	50	45	30	859	909	372	0.00
KY	1973	1.320	1.370	C		2	L		40	40	45	25	581	895	294	0.01
KY	1973	1.970	2.000	F		2	R	20	15	15	20	10	55	151	61	0.03
KY	1973	2.010	2.040	F	4	2	L	20	20	15	20	10	103	151	75	0.01
KY	1973	2.960	3.010	E		2	L		30	30	30	25	266	406	251	0.02
KY	1973	3.620	3.690	C		2	L		40	45	45	30	577	744	395	0.02
KY	1973	4.270	4.310	D		2	L		45	45	35	30	779	556	405	0.01
KY	1973	5.120	5.150	C		2	R		50	40	55	45	748	954	507	0.05
KY	1973	7.360	7.410	A		2	R		50	50	55	45	870	2291	569	0.04
KY	1973	9.740	9.780	C		2	L		50	45	45	35	690	690	524	0.02
KY	1973	11.180	11.310	D		2	R		40	55	35	55	1058	512	1170	0.02
KY	1973	11.350	11.400	E		2	L	25	25	25	30	25	190	258	194	0.04

The absolute difference for each method comparison was plotted in a histogram along with a cumulative percentile. Figure 3 shows the histogram and percentile graphs comparing DBBI and CARS. For the sake of brevity, graphs for other comparisons were not included in this report. When compared to the one featured, they exhibited lower frequencies and lower percentiles.

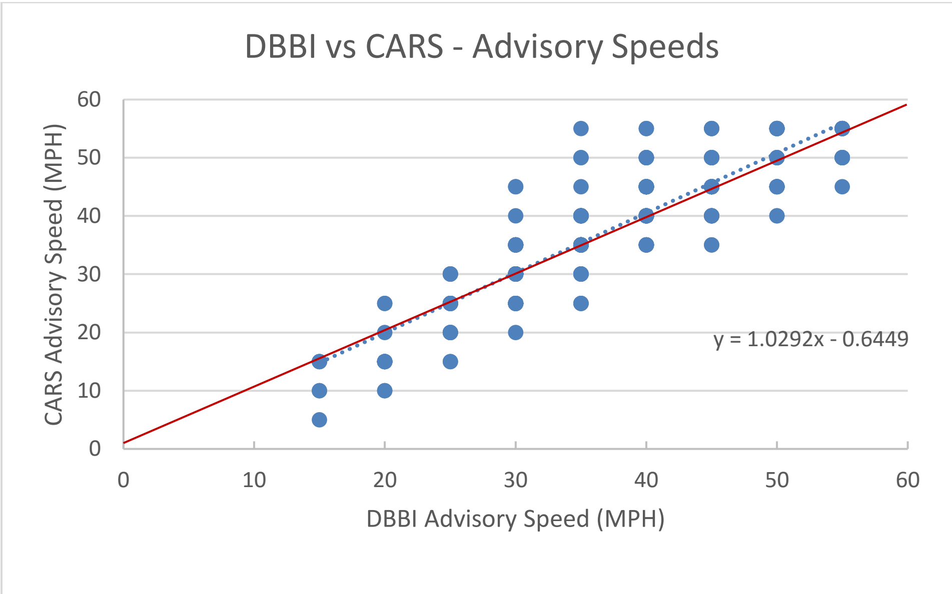
FIGURE 3 Histogram and Percentile for Digital Ball-Bank Indicator (DBBI) compared to Curve Advisory Reporting Service (CARS).



It was apparent that advisory speeds calculated with the CARS System were most similar to advisory speeds obtained using the DBBI method. For nearly half of the curves (46 percent), DBBI and CARS returned the same curve advisory speed; for 90 percent of curves, the difference was within 5 mph; and for 98 percent of curves the difference was within 10 mph. These comparisons reveal the absolute difference in speeds, however; taken alone they do not indicate the directionality of the difference. Subsequent comparisons consider the question of directionality.

Scatterplots were created to visualize the advisory speeds calculated from the DBBI and CARS, ARC, and HIS, respectively. The data points are correlated and the slope and intercept can be used to compare the two data sets. Figure 4 shows a comparison of advisory speed calculated with DBBI and with CARS. As before, scatter plots were created for three different comparisons, but only the one showing the largest correlation was included here.

FIGURE 4 Scatter Plot of Advisory Speeds for Digital Ball-Bank Indicator (DBBI) and Curve Analysis Reporting System (CARS).



The red line represents an equal association, while the dashed blue line represents the best fit linear trend. In this case, the blue line is nearly equal to y = x, indicating a near perfect correlation. This graph also indicates the directionality of the differences. Data points below the dashed line represent a speed lower than the DBBI advisory speed and data points above the line represent a speed higher than the advisory speed of the DBBI.

The actual difference (not absolute value) between the DBBI and each of the other three methods was computed and then summarized for each method and direction. There was a 3.5 to 3.8 mph discrepancy between HIS and DBBI, a 2.5 to 3.5 mph discrepancy between ARC and DBBI, and a -0.6 to -0.3 mph discrepancy between CARS and DBBI.

Evaluating the graphs and the discrepancies, CARS showed the most promising result. The other two methods tended to return more conservative estimates, generally calculating lower curve advisory speeds than DBBI. A positive difference is preferable to a negative difference in that posting a higher advisory speed is not desirable. However, it is important that signs with advisory speeds too low do not unintentionally encourage drivers to disregard advisory speeds.

Lastly, researchers compared the radii calculations from CARS, HIS, and ARC. This was included because radius has the strongest influence on chosen speed. Each radius calculation is based on GPS data. For each method the curve identification requires manual selection, however a very small percentage of HIS is based on an algorithm using the change in bearing recorded in the data points. The DBBI method does not require radius so it was excluded from these comparisons. The comparisons were used to evaluate the accuracy of radius for future research.

Scatter plots were again used to compare the radius from one method to the others. Again, a diagonal line at where y = x indicates similarity in the radii. Figures 5 through 7 show the results for each comparison.

FIGURE 5 Scatter Plot of Radii from Curve Advisory Reporting Service (CARS) and Arc Method.

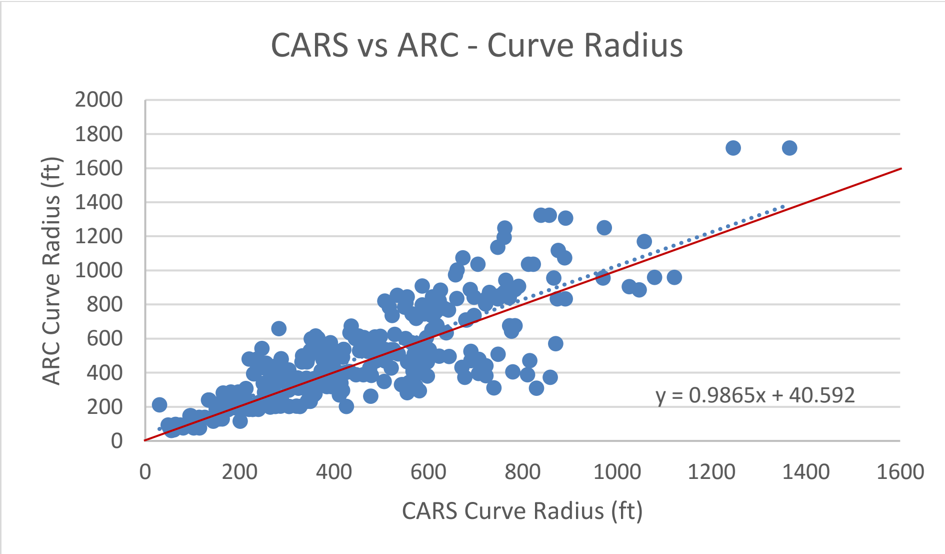


FIGURE 6 Scatter Plot of Radii from Curve Advisory Reporting Service (CARS) and Highway Information System (HIS).

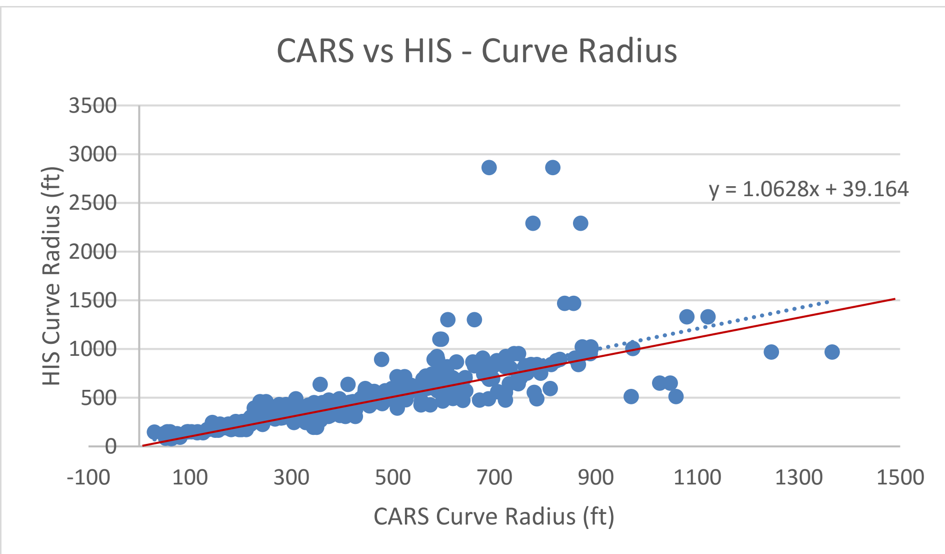
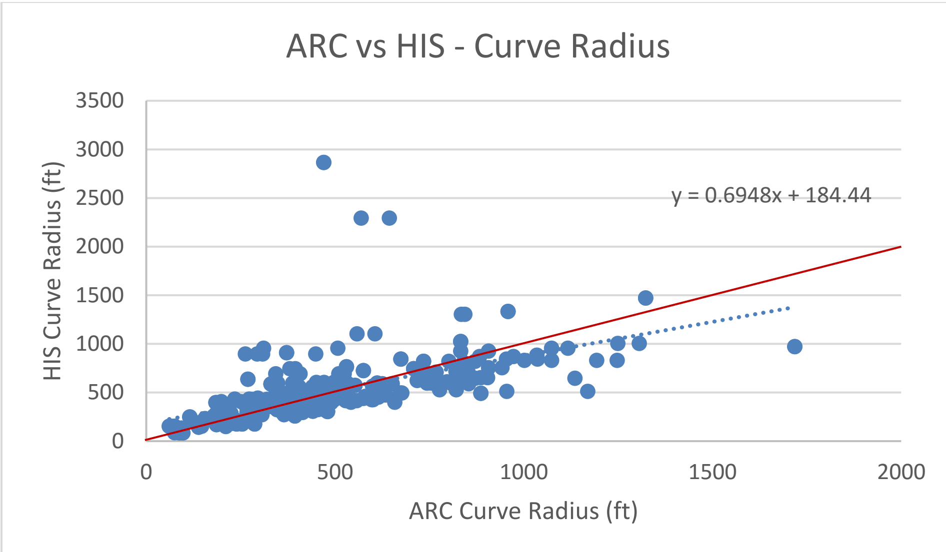


FIGURE 7 Scatter Plot of Radii from Arc Method and Highway Information System (HIS).



As with previous comparisons, red and blue lines are used to compare the data points. Data obtained from the CARS is most similar to that derived from the ARC method. This is logical given that both methods require the manual detection of curves. This comparison also helps understand the consistency of radii calculations for future research.

5 CONCLUSIONS AND RECOMMENDATIONS

The literature review, data review, and data analysis resulted in the following conclusions and recommendations.

- The DBBI method is widely used in Kentucky and, though time consuming, is an accepted method.
- Due to its efficiency and accuracy, the CARS System is the best alternative to the DBBI method.
- To determine whether to replace the DBBI method with the CARS system, KYTC officials should perform a cost-benefit analysis.
- The CARS system produces the greatest benefits when the curve frequency is high — for example, in regions with uneven topography with many horizontal curves. As such, KYTC could consider a hybrid approach that uses both CARS and DBBI.
- District 4's modified TRAMS method should be investigated in more detail. It could potentially serve as a viable alternative to CARS — especially when curve frequency is low. It should be noted that District 4 is not a particularly mountainous district so its use in this type of road has not been tested.
- When choosing a curve assessment method, KYTC staff should be mindful of the amount of time that will be needed to complete an assessment. The CARS system minimizes and simplifies field data collection, while the DBBI method can require drivers to make several passes of each curve. This requires finding a safe location to turn around, which is often cited as the most difficult aspect of this method.

Future work should investigate potential errors in the DBBI method. Errors in this method can produce misleading comparisons to other methods. The HIS and ARC methods should still be researched as well. In addition, repeatability of the results should be evaluated. It is possible that, through calibration, the advisory speeds can be improved.

6 ACKNOWLEDGMENTS

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